



# PHENIX Results in d+Au Collisions

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## Abstract

The PHENIX experiment at the Relativistic Heavy Ion Collider has performed a comprehensive set of measurements in d+Au collisions. Observables in d+Au collisions were originally conceived as a control experiment where no quark-gluon plasma is formed and one could isolate so-called cold nuclear matter effects, including nuclear modified parton distributions and parton multiple scattering. However, recent data from the PHENIX experiment in d+Au, in conjunction with new p+Pb results at the Large Hadron Collider, give strong evidence for a very different picture. We present new results that hint at the formation of a small quark-gluon plasma, that though short lived, leaves a fingerprint of evidence on final state observables. These new results will be discussed in the context of competing theoretical interpretations.

**Keywords:** quark-gluon plasma

The quark-gluon plasma is generally believed to be created in relativistic heavy ion collisions to form the hot nuclear matter. In order to study the “hot nuclear effect”, we need a baseline measurement, such as p+p collisions, which is believed there is no quark-gluon plasma being created. People also need p(d)+A collisions to study the cold nuclear effect to constrain the contributions of hot nuclear effect. From the latest p+Pb results from LHC, in most central p+Pb collisions, some behavior similar to heavy ion collisions such as long range two particle correlations [1] and angular anisotropy of particle distributions [2] are observed and make people wondering if the small systems such as p+Pb and d+Au can also create a hot nuclear matter.

In order to have some better understanding of the result in d+Au collisions, we compare the results with the peripheral Au+Au collisions with similar number of participants ( $N_{part}$  and number of binary collisions ( $N_{coll}$ ), so we have a better control of the system size with different system geometry.

The first thing we compare is the chemical composition in central d+Au collisions (0-20%) and in periph-

eral Au+Au collisions (60-92%). Fig. 1 and Fig. 2 [3] show the ratio of  $K^+/\pi^+$ ,  $K^-/\pi^-$ ,  $p^+/\pi^+$ ,  $p^-/\pi^-$  in central d+Au and peripheral Au+Au collisions. In both cases, all ratios between d+Au and Au+Au are identical as a function of  $p_T$ , which suggests the particle production mechanism of the two system should be very similar.

To further compare the difference, the ratio of spectra between d+Au and Au+Au for charged pions, kaon, proton and  $\pi^0$  are shown in Fig. 3. Starting from the lowest  $p_T$ , the ratios decreases with  $p_T \approx 2.5 \text{ GeV}/c$ . From  $p_T$  at 2.5 GeV/c and above, the ratios are flat to the same value of roughly 0.65 for each particle species. This universal scaling suggests a common production mechanism between peripheral Au+Au and d+Au collisions.

Since the  $N_{part}$  and  $N_{coll}$  are essentially the same between the two colliding systems, any quantity or physical effect which scales with these should be cancelled in the ratio. In Fig. 3, the ratio smaller than one suggests that there might be parton energy loss in peripheral Au+Au collisions. Since proton shows similar trend as pion and kaon, this indicates proton also has similar en-

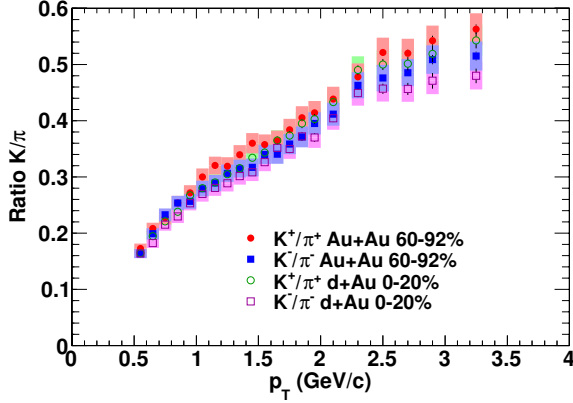


Figure 1: Ratio of  $K^+/\pi^+$ ,  $K^-/\pi^-$  as a function of  $p_T$  in central d+Au and peripheral Au+Au collisions [3].

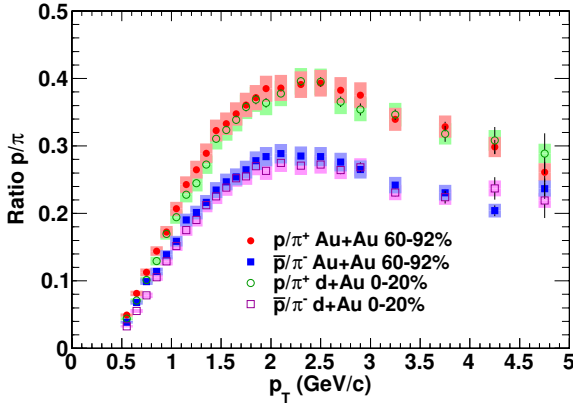


Figure 2: Ratio of  $p^+/\pi^+$ ,  $p^-/\pi^-$  as a function of  $p_T$  in central d+Au and peripheral Au+Au collisions [3].

ergy loss mechanism.

The two pion interferometry or the Hanbury Brown and Twiss (HBT) method is a standard method to extract the Gaussian radii of  $R_{out}$ ,  $R_{side}$  and  $R_{long}$  of the emission source. Here, with similar  $N_{part}$  and  $N_{coll}$ , the HBT method is used to extract the radii of peripheral Au+Au and central d+Au collisions.

Fig. 4 [4] shows the  $m_T$  dependence of  $R_{out}$ ,  $R_{side}$  and  $R_{long}$  of central d+Au (0-10%) and peripheral Au+Au (60-88%) collisions. All three radii show a decrease trend with increasing  $m_T$ .  $R_{out}$  and  $R_{side}$  shows similar trend and comparable values in both systems.

In Fig. 5(a) [4], the ratio of  $R_{out}$  and  $R_{side}$  are plotted as a function of  $m_T$ . The ratios are consistent in both systems, and are roughly flat or slightly decreasing with  $m_T$ . Since this trend is typically regarded as the result of final state rescattering effect, the similarity between the

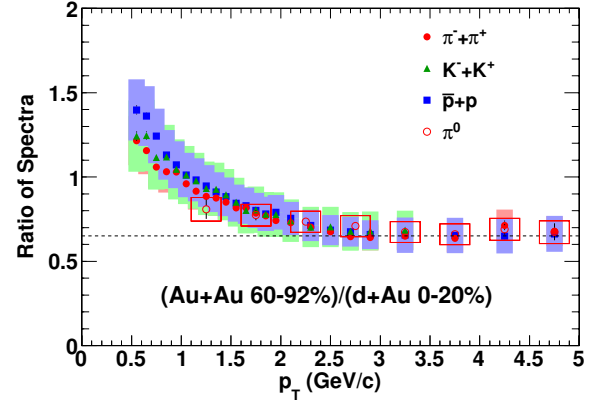


Figure 3: Ratio of invariant yield of particles in peripheral Au+Au (60-92%) to central d+Au (0-20%) collisions as a function of  $p_T$  [3].

two systems indicates both peripheral Au+Au and central d+Au collisions have similar final state dynamics.

In Fig. 5(b), the freeze-out volume of both system is measured as the product of  $R_{out}$ ,  $R_{side}$  and  $R_{long}$ . The volume decreases with  $m_T$  as expected, and volume in peripheral Au+Au is always larger than the volume in central d+Au. When taking the ratio of the two volumes as shown in Fig. 5(c), the ratio is flat as a function of  $m_T$ , which indicates a similar  $m_T$  dependence of the volume in both systems.

In some models, the expansion time,  $\tau$ , is proportional to the initial geometric size of the system,  $\bar{R}$ , which is defined as  $1/\bar{R} = \sqrt{1/\sigma_x^2 + 1/\sigma_y^2}$ , where  $\sigma_{x,y}$  is the root-mean-square width of the density profile calculated from Glauber Monte-Carlo simulations. Therefore  $\bar{R}$  may be used as a natural scaling variable. In Fig. 6(a),  $R_{side}$  of Au+Au and d+Au collisions in various centralities are plotted as a function of  $\bar{R}$ . A linear trend is seen across both systems. The result from Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$  LHC is plotted together as well. The LHC result also shows a linear trend with  $\bar{R}$ , with a larger slope compare to RHIC data, which indicates a larger expansion rate at LHC due to larger energy. In Fig. 6(b), similar dependence of  $R_{inv}$  vs  $\bar{R}$  from Pb+Pb at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$  and p+Pb at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  is plotted, and also shows a similar linear trend. This shows that Au+Au and Pb+Pb have similar final rescattering effect, and the effect also applies to d+Au and p+Pb systems as well.

One of the unique feature in two particle  $\Delta\eta$ - $\Delta\phi$  correlations in heavy ion collisions is the long range correlation in  $\Delta\phi \approx 0$ , known as “ridge”. This special struc-

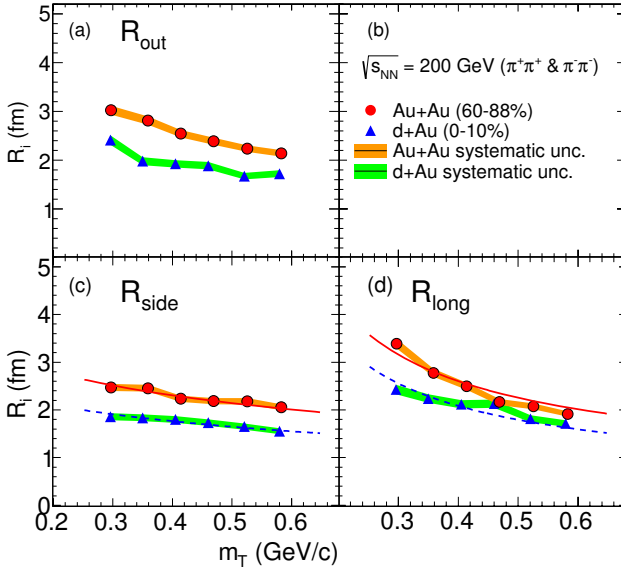


Figure 4: Comparison of  $m_T$  dependence of  $R_{out}$ ,  $R_{side}$  and  $R_{long}$  [4].

ture is originally believed to exist only in central heavy ion collisions, and was regarded as a result of higher order harmonics of flow coefficients. But measurements at LHC shows that in high multiplicity p+p collisions at 7 TeV [10] and p+Pb at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  [1], the ridge structure has also been observed. This makes people wondering if the tiny system such as p+p and p+Pb can also behave like a hot nuclear matter as in heavy ion collisions. Moreover, if similar phenomena can be observed in d+Au collisions at a much lower RHIC energy.

Fig. 7 [9] shows the two particle  $\Delta\phi$  correlations in central d+Au and p+p collisions with  $\Delta\eta$  at least 3 units away from each other. In p+p collisions, since two particles are separated with at least 3 units in  $\eta$ , we expect there is no correlations in  $\Delta\phi \approx 0$ . In  $\Delta\phi \approx \pi$  we expect there is correlations corresponds to the away-side jet. This is exactly what we see in the right-hand side of Fig. 7. When we look at the same correlation function in central d+Au collisions in the left-hand side of Fig. 7, we see there is a significant enhancement in  $\Delta\phi \approx 0$  which is consistent with the “ridge”. The ridge exists through a wide range of  $p_T$  from 0.2 to 4.0 GeV/c.

We measured the Fourier spectra of the correlation functions in Fig. 7, and the results are also plotted on Fig. 7. In p+p collisions, the correlations are described well with  $c_1$ , which also corresponds to the conservation of momentum. The rest of the coefficients are consistent with 0. In d+Au collisions, the correlations

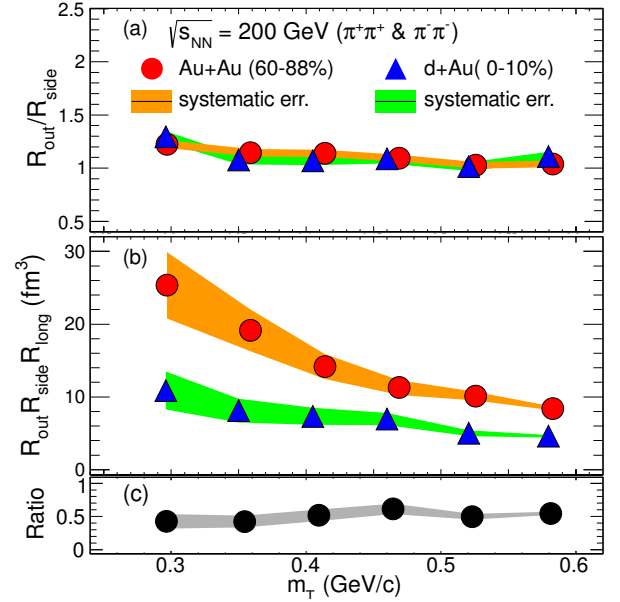


Figure 5: Comparison of the  $m_T$  dependence of; (a) the ratio  $R_{out}/R_{side}$ ; (b) the freeze-out volume, and (c) the ratio of the freeze-out volumes, for 0-10% central d+Au and 60-88% central Au+Au collisions [4].

are described with  $c_1$  and  $c_2$ , which means it also have some significant elliptic flow like contribution in central d+Au collisions.

In order to measure the  $v_2$  in central d+Au collisions accurately, PHENIX measured the  $v_2$  with event plane method with event plane measured with Muon Piston Calorimeter at  $-3.7 < \eta < -3.1$  facing Au-going direction. The result is shown in Fig. 8 as red points. The result is lower than the other PHENIX  $v_2$  measurement with two-particle correlation method (blue points) [8], which might still suffered by some remaining non-flow contributions. When comparing with the p+Pb results from LHC, the d+Au  $v_2$  is slightly higher, which may due to the difference of the initial state geometry.

In summary, systematic studies in central d+Au and peripheral Au+Au collisions are performed in PHENIX. Central d+Au and peripheral Au+Au collisions have similar particle compositions, which suggests similar particle production mechanism. From HBT correlation measurements, peripheral Au+Au has larger freeze-out volume than central d+Au collisions, and similar trends of the radii in  $m_T$  indicates similar final state rescattering effect in both systems. Besides all these, the central d+Au collisions also have some flow-like behavior, where the size of  $v_2$  is compatible to p+Pb collisions at

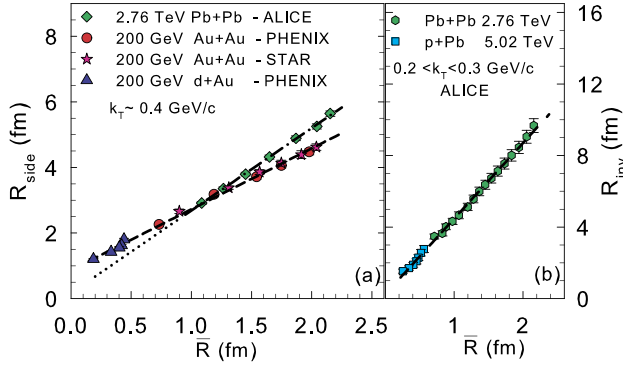


Figure 6: (a)  $R_{side}$  vs  $\bar{R}$  in Au+Au, d+Au and Pb+Pb collisions.; (b)  $R_{inv}$  vs  $\bar{R}$  in Pb+Pb and p+Pb collisions [4, 5, 6, 7].

higher energy.

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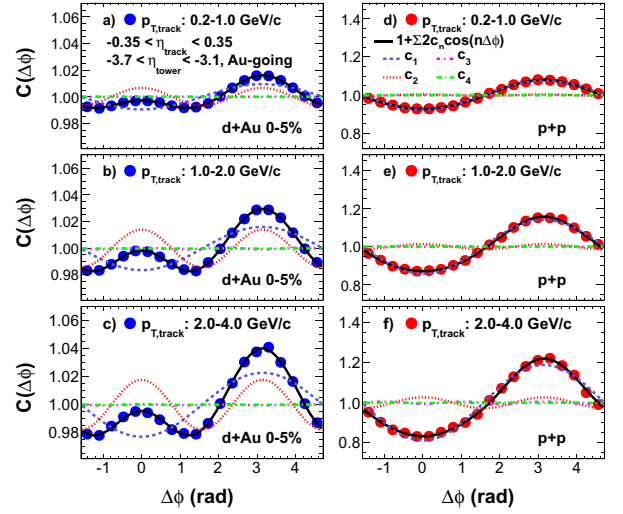


Figure 7: Long range  $\Delta\phi$  correlations of central d+Au and p+p collisions [9].

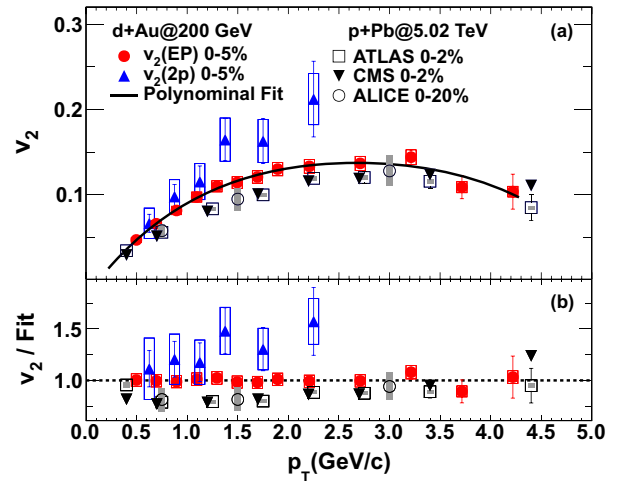


Figure 8:  $v_2$  of central d+Au collisions vs  $p_T$ .